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DESIGN OF SIDE WALLS IN CHUTES AND SPILLWAYS

By D. B. Gumensky, M. ASCE

HYDRAULICS DIVISION

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AMERICAN SOCIETY OF CIVIL ENGINEERS

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PAPERS

DESIGN OF SIDE WALLS IN CHUTES AND SPILLWAYS

By D. B. Gumensky,[1] M. ASCE

Synopsis

Water confined between vertical walls and flowing down an inclined plane exerts a lateral pressure of diminishing intensity on the walls as the steepness of the fall increases. The limit in such a case is a vertical fall when the lateral pressure equals zero.

When the flow of water is deflected by a vertical curve as at the bottom of a chute or in a "flip bucket" of a spillway, the centrifugal force increases the pressure on the bottom and on the walls of the confining channel. The effect of this increase in pressure is as though the water were much denser than it really is—in some actual cases as much as twelve times the density of water.

Introduction

When designing chutes, wasteways, and spillways, the hydraulic design is the first and the most important phase. The structural design follows the completion of the hydraulic design. In the structural design, the principal features are the thickness and the reinforcement of the side walls and (in spillways where they are used) of the intermediate training walls. It has been the writer's experience that much time is spent in discussing and in determining the proper criteria for the design of these walls. Because little treatment of this subject has been found in engineering literature, this presentation is submitted in the hope that it may help the practicing engineer both to save time in getting the job done and to save his client a considerable amount of money. The usual engineering practice, because of a lack of understanding, is to over-design such walls by about twice the necessary requirement. On the other hand, the effect of the centrifugal force in deflected streams is seldom evaluated and the walls often remain standing in a condition near failure.

Note.—Written comments are invited for publication; the last discussion should be submitted by August 1, 1953.

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Pressure in Still Water

The intensity of pressure in still or slowly moving water varies directly with the depth and equals the depth times the specific weight (see Fig. 1). This pressure is expressed as

$$p = \gamma h = 62.5\, h \qquad (1a)$$

in which p equals the intensity of pressure, in pounds per square foot; γ equals the weight of water, in pounds per cubic foot; and h equals the depth of water from the surface, in feet.

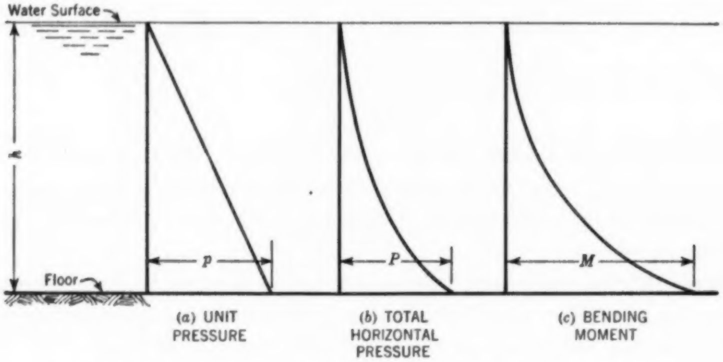

Fig. 1.—Pressure and Moment on a Vertical Wall in Still Water

In this case, the total horizontal pressure on a unit length of a vertical wall will be

$$P = \tfrac{1}{2}\gamma h^2 = 31.2\, h^2 \qquad (1b)$$

in which P equals the total pressure, in pounds per unit length of wall. The moment about the base of the wall caused by this pressure will be

$$M = \tfrac{1}{6}\gamma h^3 = 10.4\, h^3 \qquad (1c)$$

Pressure in a Steeply Inclined Stream

In a stream flowing down a steeply inclined slope, the pressure pattern is modified from the static condition. The water, which is supported on a slope, has a negligible shearing value. Therefore, the floor supports only the normal component of the weight of the water.

The component of the weight parallel to the floor is used either to accelerate the water down the slope or to overcome friction, or both. This condition is illustrated in Fig. 2. The shaded unit volume of water weighs γ pounds. This weight is resolved into components that are normal and parallel to the floor. The component of the weight parallel to the floor produces no pressure and is expended in producing acceleration down the slope and in overcoming friction. The component of the weight normal to the floor produces the

pressure on the floor (and on the walls) and equals in value the weight multiplied by the cosine of the angle which the floor makes with the horizontal. Measuring the depth of water in the direction normal to the floor, and using the subscript α to designate the inclined floor and stream, the pressure intensity at the floor becomes

$$p_\alpha = \gamma h \cos \alpha \qquad (2a)$$

The value of h is modified by the cosine of the angle only in the evaluation of the intensity of the pressure. In computing the total horizontal pressure on an element of a wall, the pressure intensity acts over the full value of h so

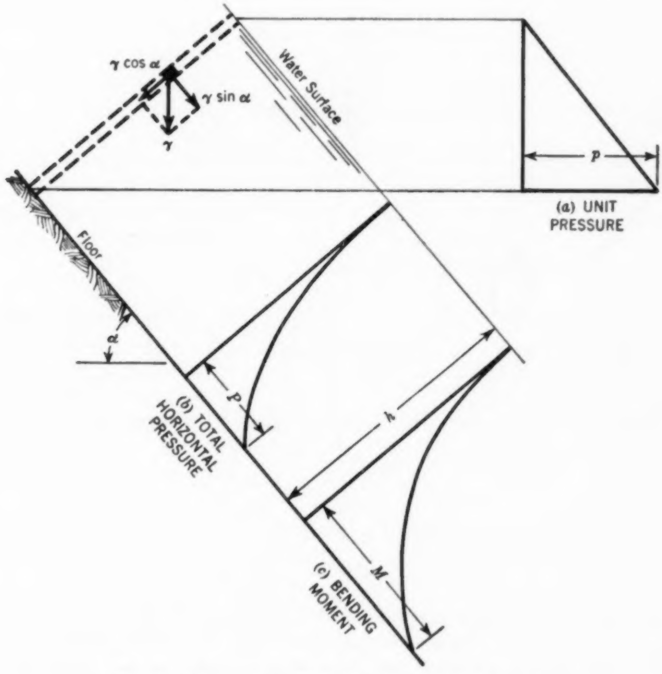

FIG. 2.—PRESSURE IN WATER FLOWING ON AN INCLINE

that the overturning force becomes

$$P_\alpha = \tfrac{1}{2} \gamma h^2 \cos \alpha \qquad (2b)$$

and the overturning moment is expressed as

$$M_\alpha = \tfrac{1}{6} \gamma h^3 \cos \alpha \qquad (2c)$$

The fallacy of using the vertical depth for determining pressures of flowing water on steep slopes, as is done by some engineers, becomes apparent at the limiting condition of the slope. If the floor were vertical, the water would fall

down within the confinement of the floor and the walls. Any pressure developed on these confining surfaces would be merely nominal.

PRESSURE IN A DEFLECTED STREAM

If a flowing stream is deflected by a curving vane, such as a vertical curve in a chute or a flip bucket at the bottom of a spillway, the pressure of the water is increased by centrifugal force. This increase in pressure may be easily evaluated. If a bucket of water is rotated in a vertical plane as shown in Fig. 3, and, if F_c represents the centrifugal force, ρ is the mass per unit volume of water, ω denotes the angular velocity in radians per second, and r equals the radius of curvature, in feet, then

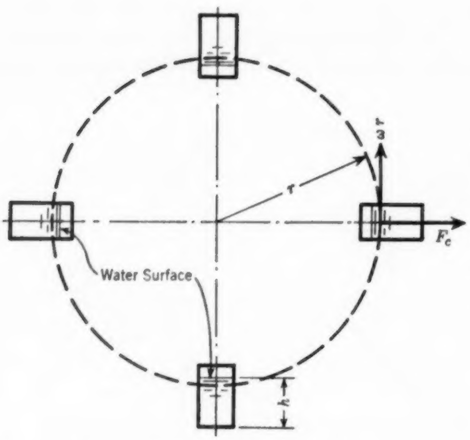

FIG. 3.—CENTRIFUGAL FORCE ON WATER IN ROTATING BUCKETS

$$F_c = \rho\, \omega^2 r \quad \ldots\ldots (3)$$

Considering an element of the water in the bucket of Fig. 3, having a cross-sectional area (dA), of one square foot and a depth h, the mass of water in the bucket is expressed as

$$\rho = \frac{\gamma\, h\, dA}{g} = 1.94\, h \quad \ldots\ldots (4)$$

Substituting this value of ρ into Eq. 3 yields

$$F_c = 1.94\, \omega^2\, r\, h \quad \ldots\ldots (5)$$

From Eq. 5 it is apparent that the centrifugal force will not only vary directly as ω^2 and as r, but will also vary directly as h. This also can be deduced logically from Eq. 3 because the mass of the water in the container varies directly with the depth h and, therefore, the centrifugal force varies directly with h. Further examination of Eq. 5 shows that the expression $1.94\, \omega^2\, r$, on the right-hand side of the equation, is equivalent to the unit weight of a liquid in the expression for hydrostatic pressure at depth h.

For the specific case of a flip bucket at the bottom of the spillway of Pine Flat Dam, on Kings River, in California, which the writer helped to design, the velocity of water was 139 ft per sec and the radius of the flip bucket was 50 ft. Substituting these values in Eq. 5, $F_c = 1.94 \left(\frac{139}{50}\right)^2 50\, h = 749\, h.$

Comparing the value 749 lb per ft with 62.5 lb per ft makes obvious the fact that the centrifugal pressure of the water in the flip bucket is equal to the

static pressure created by a liquid having a specific gravity about twelve times that of water. Considering the static pressure, which is not included in the formula for centrifugal pressure, the wall of the flip bucket should be designed for a loading equal to thirteen times the loading on an equivalent wall holding static water to the same depth as the flow depth in the bucket.

The unit liquid pressure for which the side walls should be designed in concave vertical curves of chutes or flip buckets (Fig. 4) is expressed by the equation

$$p_{vc} = (1.94\,\omega^2 r + 62.5)\,h \quad \text{(6a)}$$

The total horizontal pressure on the unit length of the wall then becomes

$$P_{vc} = \tfrac{1}{2}\,p_{vc}\,h^2 \quad \text{(6b)}$$

and the bending moment at the base of wall—

$$M_{vc} = \tfrac{1}{6}\,p_{vc}\,h^3 \quad \text{(6c)}$$

Convex curvatures exist at the tops of spillways and in some chutes. In such cases, the forces acting on the element of the water are the weight of the water, the kinetic force of the stream, the restraining effect of walls, and the support of the bottom.

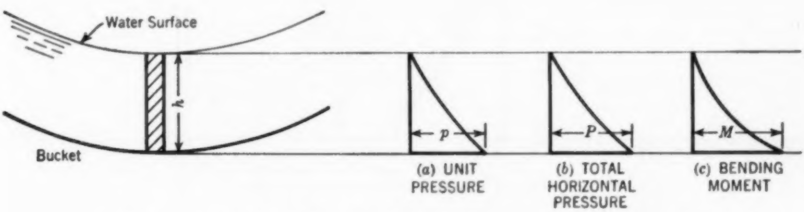

FIG. 4.—PRESSURE IN WATER FLOWING IN A CIRCULAR VERTICAL CURVE

Sometimes the convex curvature of the bottom is so sharp that the acceleration of the force of gravity is insufficient to make it follow the bottom. The stream then tends to separate from the bottom and negative pressures result. The water pressures on side walls in such cases are reduced to nominal resistance to confinement, and the stream temporarily acts as a jet. All cases of convex curvature can be investigated graphically very easily and quickly.

EFFECT OF AIR ENTRAINMENT

At velocities of about 20 ft per sec and faster, air becomes entrained in the water, swelling its volume and increasing its depth. Numerous measurements were made on fast flowing water in chutes and spillways, and some correlation between velocity and air entrainment was established.[2] However, there are no experimental data on the distribution of pressure in such "white water." Some idea of it can be gleaned from logical reasoning based on physical facts.

[2] "Air Entrained in Fast Water Affects Design of Training Walls and Stilling Basins," by D. B. Gumensky, *Civil Engineering*, December, 1949, p. 35.

In Fig. 5, the probable pressure distribution in a stream with entrained air is illustrated. Because the weight of the water supported by the floor is the same whether or not there is entrained air, the intensity of the pressure on the bottom of the channel will be $\gamma\ h$ for both cases. The intensity of the pressure at any position above the floor is equal to the weight of the water above a horizontal unit area at that level. For a uniform mixture of air and water (extreme hypothesis), the intensity at any depth will be represented by the straight line 2–4. Since the volume of the entrained air is a maximum near the surface and gradually diminishes toward the bottom, the actual pressure will be represented by some curve 2–5–4 between lines 2–4 and 2–1. However, because of the varying ratio between distances 1–4 and 1–3, depending on the velocity and the depth of the flow, the writer was unable to find any general curve equation which would be suitable for all conditions. For design purposes, it seems best to use the extreme hypothetical assumption of the

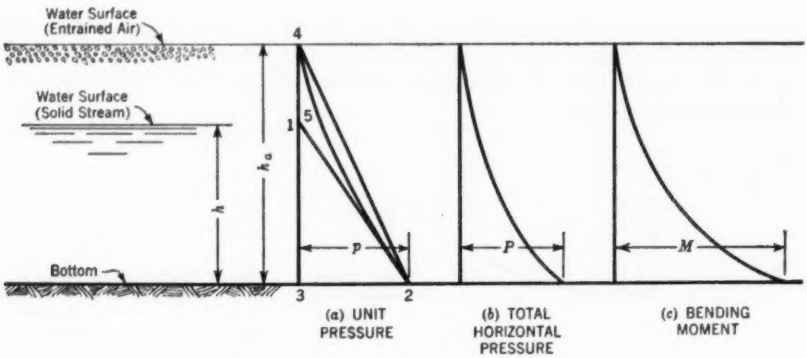

Fig. 5.—Pressure in Water with Entrained Air

uniform air distribution as represented by line 2–4, which errs on the side of safety. Because the flow with air entrainment occurs on steep slopes, the correction for the vertical angle is introduced. Substituting lighter unit weight, $\gamma_a = \gamma \frac{h}{h_a}$ for the water-air mixture, and using the subscript a for the flow of water with entrained air, the design equations become

$$p_a = \gamma\ h \cos \alpha \quad \text{(7a)}$$

$$P_a = \tfrac{1}{2}\ \gamma\ h\ h_a \cos \alpha \quad \text{(7b)}$$

and

$$M_a = \tfrac{1}{6}\ \gamma\ h\ h^2_a \cos \alpha \quad \text{(7c)}$$

Although specific data are not available, it appears that, when a stream with entrained air is deflected by a vertical curve, the centrifugal force tends both to drive the air out of the stream and to force it into solution. Therefore,

until data are available showing the effect of vertical curves on air entrainment, the design of walls in vertical curves should be based on Eqs. 7. Fig. 6 illustrates the flow of water with entrained air down the face of a spillway and through a flip bucket at the bottom of the spillway. (This photograph was

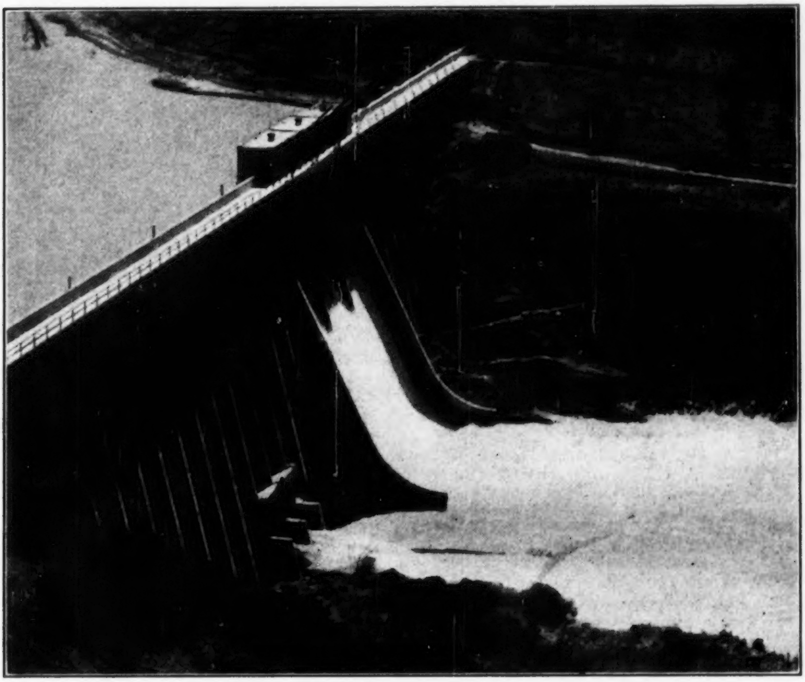

FIG. 6.—STONY GORGE DAM, ORLAND PROJECT (UNITED STATES BUREAU OF RECLAMATION), CALIFORNIA

kindly supplied by the Denver (Colo.) office of the Bureau of Reclamation.) It shows the swelling of the stream caused by air entrainment, with subsequent vertical contraction in the flip bucket in which the air is partly driven out by centrifugal force.

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